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Some Climatological Aspects of the Circulation in Southern Hemisphere Temperate Latitudes as Determined From 200-Millibar GHOST Balloon Flights

J. K. ANGELL—*Environmental Research Laboratories, NOAA, Silver Spring, Md*

ABSTRACT—The climatology of the 200-mb flow in Southern Hemisphere temperate latitudes is investigated for a 1-yr period using data obtained from nine global horizontal sounding technique (GHOST) balloon flights in 1966–67. In the mean for the year, the west wind is a maximum over the Indian Ocean and a minimum near Cape Horn while a mean equatorward flow of about 1 m/s exists over the South Atlantic and a mean poleward flow of similar magnitude exists near South Africa. The poleward eddy flux of westerly momentum produced by wave numbers 1–4 is a maximum over the South Atlantic. Between 40° and 60°S, semiannual and annual variations in zonal and meridional wind are of similar magnitude, resulting in a west-wind maximum near the vernal equinox and a secondary maximum near the autumnal equinox. The inferred mean meridional velocity attains values of 0.3 m/s, with equatorward flow indicated as occurring in summer and autumn (when the west wind is relatively weak) and poleward flow in winter and spring (when the west wind is relatively strong). It is hypothesized that the mean equatorward flow results statistically from the occasional establishment of regions of inertial instability on the anticyclonic shear sides of strongly diffluent troughs and the mean poleward flow from the occasional excess of pressure gradient force over Coriolis force following air parcels moving into the anticyclonic shear zone of strongly confluent troughs. The time rate of change of zonal wind between 40° and 60°S is well correlated with the GHOST-derived convergence of meridional eddy momentum flux in this belt, but the inferred mean meridional velocity helps balance momentum accounts and helps explain the observed large semiannual variation in zonal wind.

1. INTRODUCTION

Because of the modern-day emphasis on global meteorology, considerable effort has been devoted in recent years to the study of the atmospheric circulation in the Southern Hemisphere. Papers by van Loon (1965, 1967*b*), Taljaard (1967), van Loon and Jenne (1969), and others have greatly enhanced our knowledge of atmospheric processes in this oceanic hemisphere. Recently, van Loon et al. (1971) published the second volume of what probably will become the standard climatological reference for the Southern Hemisphere for the next decade.

The above analyses have been based on conventional surface and rawinsonde observations. Well known, however, is the fact that a sufficient density of observations, particularly upper air observations, is realized over only limited portions of the Southern Hemisphere (viz over populated land masses). Various techniques for filling the data gaps have been suggested. One of these is the global horizontal sounding technique (GHOST) developed by the National Center for Atmospheric Research. This technique involves the flying of many constant-level balloons (constant-volume mylar [1] balloons) at various heights in the Southern Hemisphere (Lally et al. 1966).

During 1966–67, eight GHOST flights were launched from Christchurch, New Zealand, and one from McMurdo Sound, Antarctica, each of which remained at the 200-mb surface for at least 3 mo (Solot 1968). Balloon positions were estimated at local noon by means of telemetered sun-angle data (Lichfield and Frykman 1966). These positions are believed to be accurate to within about 100 km in temperate latitudes but are considerably less accurate in low latitudes. Of course, balloon positions cannot be obtained during the polar night. Analyses of the resulting data, from somewhat different points of view, have been presented by Solot and Angell (1969*a*, 1969*b*), Kao and Hill (1970), and Wooldridge and Reiter (1970).

Between June 1, 1966, and June 1, 1967, at least three GHOST balloons were aloft simultaneously, furnishing limited information on the variation of wind with longitude. For this 1-yr period, the purpose of this paper is to examine closely the longitudinal and temporal variability of the GHOST-derived zonal and meridional wind in Southern Hemisphere temperate latitudes as well as the variability of other parameters that may be obtained from the GHOST data. In particular, an examination is made of the GHOST-derived mean meridional velocity; through the use of the momentum balance equation, evidence is presented supporting the reality of this inferred mean velocity.

The data base for this paper consists of 24-hr-average Lagrangian values of zonal and meridional velocity for the stated 1-yr period. While obvious, it is emphasized that a 24-hr-average Lagrangian meridional velocity represents a considerable underestimate of the true meridional velocity because the meridional velocity frequently changes sign during a 24-hr period. As a consequence, the values of meridional velocity subsequently presented

[1] Mention of a commercial product does not constitute an endorsement.

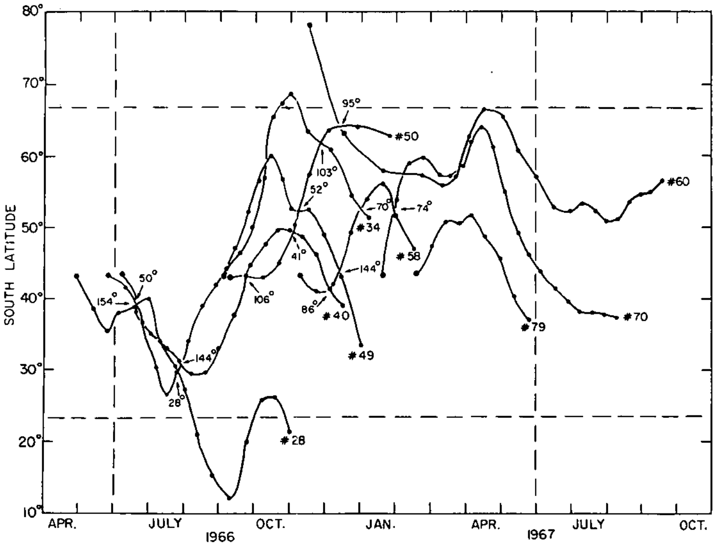

FIGURE 1.—Mean latitude of the nine GHOST balloon flights at 200 mb in the Southern Hemisphere as a function of date.

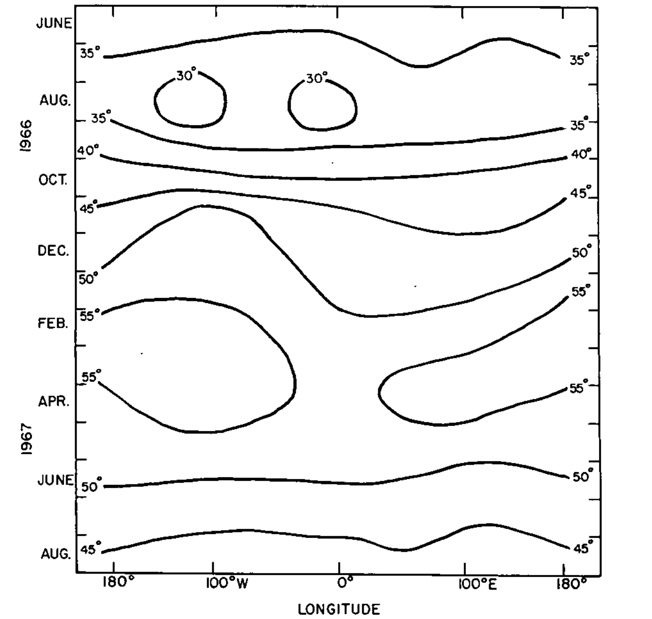

FIGURE 2.—Variation of mean GHOST balloon latitude (° S) with longitude and date.

should always be treated with caution. This bias in meridional velocity also results in a large underestimate of the meridional eddy momentum flux.

2. DATA COVERAGE

Figure 1 shows the mean latitude of the nine 200-mb GHOST flights as a function of date, obtained by averaging the latitudes for each circumnavigation of the hemisphere. In this figure, the flight number is indicated at the end of each trace. Also indicated is the longitudinal separation (in deg.) of flights moving meridionally in opposite directions at the same latitude and time. The vertical dashed lines delimit the times at which three or more flights were aloft simultaneously; the horizontal dashed lines indicate the limits of the temperate latitudes. In most cases, the balloons remained basically within the temperate latitudes as customarily defined; but there was an obvious tendency for the ballons to float farther south (nearer the South Pole) in the Southern Hemisphere summer than in winter. As a result, these particular GHOST flights did not provide uniform data coverage over Southern Hemisphere temperate latitudes, the resulting data being sparse near the Tropics in summer and sparse near the polar regions in winter.

A striking feature of figure 1 is the tendency for individual balloons to move uniformly southward or northward for periods of a few months. It is this tendency that is partly responsible for the data bias mentioned in the preceding paragraph; later on, we consider whether or not these balloon motions reflect mean meridional air motions. In this context, a puzzling observation from figure 1 is that balloons aloft at the same time and at the same latitude frequently move meridionally in *opposite* directions. The average longitudinal separation of the balloons at this time (5-day average) is indicated in figure 1 and appears to center around 90°. It is not at all apparent why a difference in the sense of meridional drift should occur at such longitudinal separations (or indeed at any longitudinal separation); some doubt is thereby cast on the representativeness of the mean meridional velocity derived from only a few GHOST balloon flights. Is it possible, for example, that the oppositely directed meridional drifts simply reflect a large-scale turbulence or random walk phenomenon and that many balloons must be aloft simultaneously before a true mean meridional motion can be determined? Whatever the answer, the above findings should be kept in mind during the subsequent discussion of GHOST-derived mean meridional velocity.

If there are large-amplitude, quasi-stationary waves around the hemisphere, then another data bias may develop because the balloons will follow the air flow around trough and ridge and not sample the nearby light-wind areas. To examine this possibility, we have averaged the latitudes of the GHOST trajectories at 60° longitude intervals around the hemisphere by month, with the results presented in figure 2. Only in summer is there an appreciable variation in mean flight latitude around the hemisphere, with the balloons near 100°W (close to the longitude of Cape Horn) floating about 5° farther south than around the remainder of the hemisphere. Certainly, however, the data bias introduced by the longitudinal variation of mean flight latitude at a given time is small compared with the bias introduced by the variation in mean flight latitude with season.

3. TIME-LONGITUDE DIAGRAMS

One of the alternative ways of presenting constant-level balloon data is by means of time-longitude diagrams as illustrated by Wooldridge and Reiter (1970). By following their procedure, 24-hr-average zonal and merid-

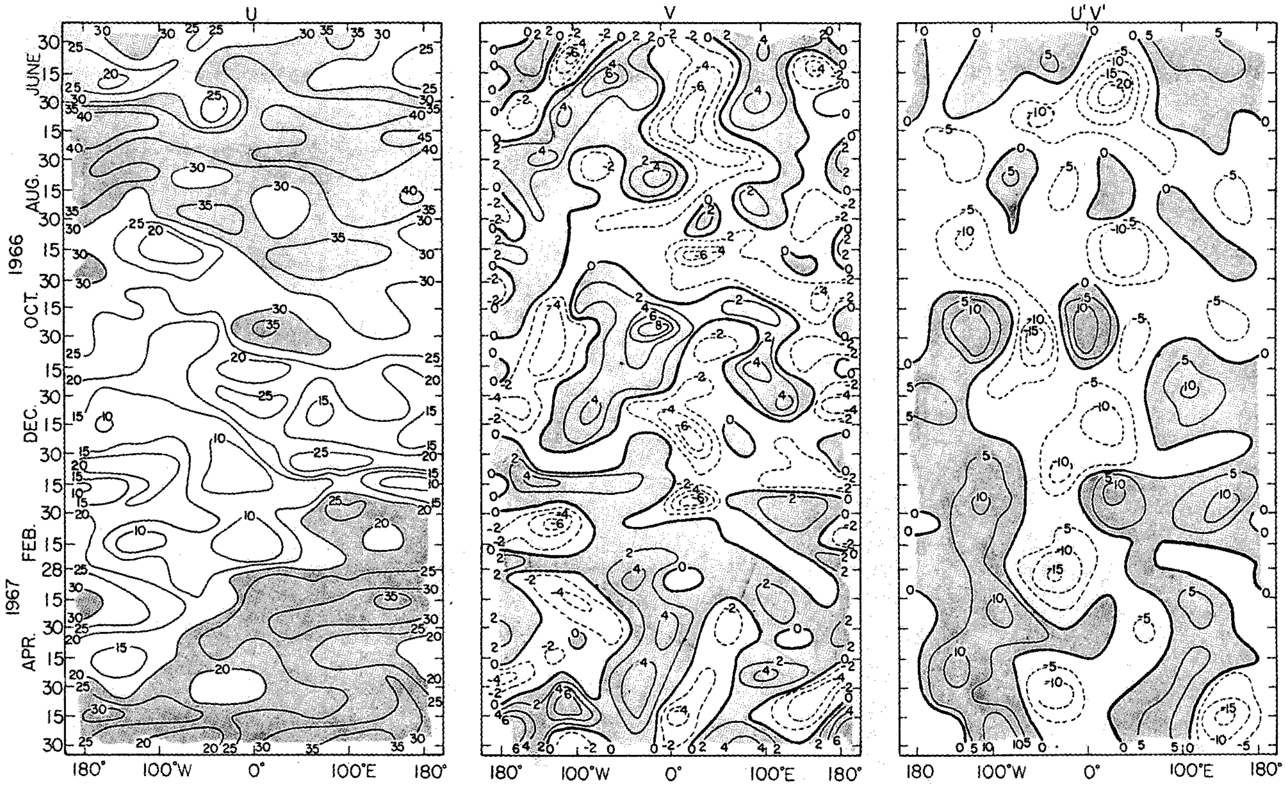

FIGURE 3.—Variation with date and longitude of the smoothed zonal (left) and meridional (middle) velocity (in m/s) obtained from GHOST balloon flights in Southern Hemisphere temperate latitudes between June 1, 1966, and June 1, 1967 (flow from the west and south is considered positive); at the right is the derived zonal-meridional eddy velocity covariance ($m^2 \cdot s^{-2}$) where a negative covariance indicates eddy momentum flux toward the South Pole.

ional velocities were plotted as a function of longitude and date; average values were determined for "boxes" encompassing 20° of longitude and 10 days of time. Since on occasion there were only three GHOST balloons aloft during the 1-yr period under study, some of these boxes had no data within them; for ensuring a complete grid of data, it was necessary to combine these boxes into four-box sets encompassing 40° of longitude and 20 days of time. These larger boxes were overlapped so that data were still available at 20° longitude and 10-day time intervals. With a 40° longitude smoothing, it obviously is satisfactorily possible to delineate only hemispheric wave numbers 1–4. Similarly, a 20-day smoothing effectively eliminates from consideration the fast-moving (about 10° long. per day) short waves in the westerlies. It is emphasized that only the gross features of the circulation in Southern Hemisphere temperate latitudes are under discussion here.

The left and middle diagrams of figure 3 show for the 1-yr period the large-scale variations of zonal and meridional wind in Southern Hemisphere temperate latitudes. For clarity, the shading extends to different zonal velocities in the upper and lower portions of the left diagram where the shading delineates the slow eastward progression of strong west winds near the vernal equinox (September) and the slow westward progression near the autumnal equinox (March). The reader is cautioned that the indicated variation of west wind with time of year in this diagram is excessive due to the variation in mean flight latitude (fig. 1).

The meridional wind diagram in figure 3 occasionally provides evidence for a quite rapid eastward wave propagation (i.e. at the end of September and in the middle of February to the east of the Greenwich Meridian); more apparent, however, are slow westward phase propagations, particularly in the South Atlantic during spring and autumn. These retrogressions are somewhat similar to those associated with blocking situations on Northern Hemisphere 5-day-mean maps, but they appear even more prolonged and of larger scale.

Since zonal and meridional velocities at 20° longitude intervals are available at 10-day intervals from the left and middle diagrams of figure 3, an approximation to the meridional eddy momentum flux induced by the long waves can be obtained at 10-day intervals from the covariance of the deviation of zonal and meridional velocities from their mean values around the hemisphere. The right diagram of figure 3 shows this derived covariance as a function of date and longitude where a negative covariance signifies eddy momentum flux toward the South Pole. Because of the great smoothing in zonal and meridional velocity with longitude and time, this derived flux is but a fraction of the flux actually occurring (Obasi 1963, 1965). Nevertheless, the tendency for surges of poleward momentum flux to occur over the South Atlantic throughout the year is impressive, as is the tendency for equator-

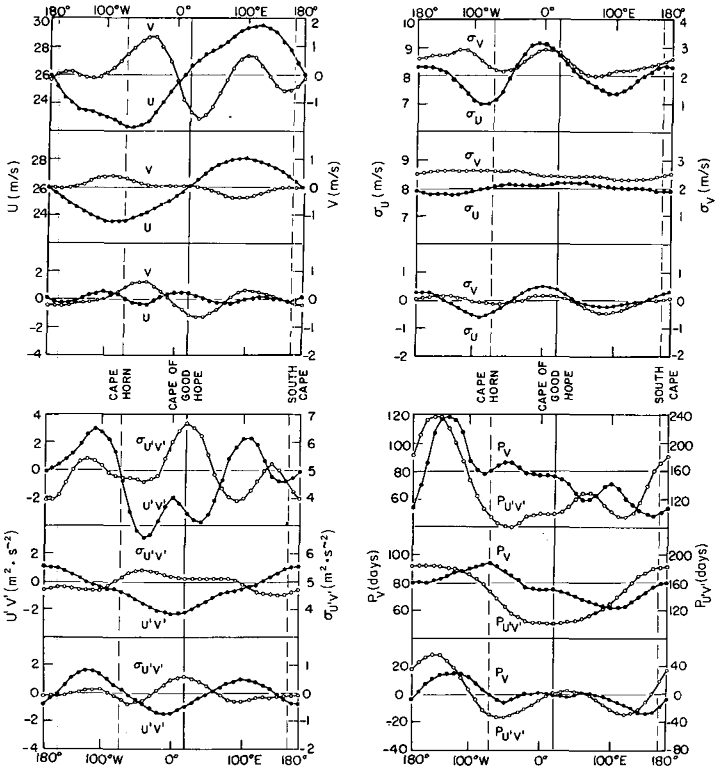

FIGURE 4.—Variation with longitude in Southern Hemisphere temperate latitudes of the 200-mb zonal and meridional velocity for the year (upper left set), the temporal standard deviation of zonal and meridional velocity for the year (upper right set), the meridional eddy momentum flux and its temporal standard deviation (lower left set), and the dominant period of oscillation of meridional velocity and eddy momentum flux (lower right set).

ward eddy fluxes to occur consistently over the southeast Pacific.

4. LONGITUDINAL VARIATION OF METEOROLOGICAL PARAMETERS

Figure 4 shows for the 1-yr period the variation with longitude of zonal and meridional velocity and their eddy covariance obtained by averaging the data of figure 3 along each meridian. Also indicated in figure 4 is the variation with longitude of the temporal variability of these parameters as expressed by respective standard deviations as well as the variation of dominant periodicities evaluated from the autocorrelation coefficients. In figure 4, the west and south winds and the northward-directed eddy momentum fluxes are considered positive. The middle and bottom diagrams of each set give the approximate contributions of wave numbers 1 and 2 to the observed longitudinal variability. An estimation of the contribution of wave number 1 to the longitudinal variability has been obtained by taking 180° longitude running means; an estimation of the contribution of wave number 2 has been obtained from the difference between 90° and 180° running means. In these diagrams, the longitudes of Cape Horn, Cape of Good Hope, and South Cape (New Zealand) have been entered for reader orientation.

Let us first examine the variation with longitude of the year-average zonal and meridional velocity as presented in the upper left diagrams of figure 4. The variation of zonal wind around the hemisphere in Southern Hemisphere temperate latitudes reflects mainly a one-wave pattern with the west wind strongest (nearly 30 m/s) over the Indian Ocean and weakest (about 22 m/s) near Cape Horn. Earlier, van Loon (1964) found that the west wind appeared to be strongest in the Indian Ocean area at the surface and 500 mb. One may conjecture that the speed minimum near Cape Horn is partly associated with the increased frictional drag induced by the Andes Mountains. In the case of the meridional velocity, a sort of 2.5-wave pattern is delineated around the hemisphere in the annual average with a mean northward velocity in the South Atlantic of about 1 m/s (presumably induced by the Andes Mountains), a similar southward velocity at the longitude of South Africa, and smaller northward and southward velocities west of Australia and over New Zealand, respectively. There is a tendency for the northward velocity to be greater in summer than in winter over the South Atlantic and smaller elsewhere (apparent from fig. 3) and for the west wind to be stronger in winter than in summer in most longitudes, especially over the South Atlantic.

In the mean for all longitudes, an average annual northward drift of 1.8 cm/s is obtained, furnishing some evidence for the extension of the Ferrel cell to 200 mb. The indicated mean northward drift is somewhat larger in winter (2.6 cm/s) than in summer (1.0 cm/s).

Comparison of the longitudinal variation of zonal and meridional velocity shows that the year-average standing waves contribute to the poleward momentum flux. Thus, the correlation of −0.40 between the west and south winds around the hemisphere (table 1) emphasizes the fact that, over the Indian Ocean where the west wind is strong, there tends to be a southward drift of air and that, over the South Atlantic and southeast Pacific where the west wind is weak, there tends to be a northward drift of air. In the case of wave number 2, the correlation between west and south winds is −0.77, suggesting that this wave number contributes appreciably to the poleward flux of westerly momentum.

The upper right diagrams of figure 4 show the standard deviation of zonal and meridional velocity (for the year) as a function of longitude. Large values of the standard deviation result mainly from large seasonal changes in the velocities at the given longitudes; in general, large seasonal changes in the zonal wind are accompanied by large seasonal changes in the meridional wind (correlation $r=0.43$ from table 1). The seasonal variability tends to be large over the South Atlantic and relatively small near Cape Horn, the latter suggesting the influence of the Andes Mountains in stabilizing the flow. Table 1 also indicates that, at longitudes where the west wind is strong in the yearly average, the yearly variability of meridional wind is small ($r=-0.44$).

The heavy lines in the lower left diagrams of figure 4 show the variation with longitude of the zonal-meridional

TABLE 1.—*Correlations between the longitudinal variations of year-average west (U) and south (V) winds, the northward eddy flux of momentum (U'V') and its temporal standard deviation ($\sigma_{U'V'}$), the temporal standard deviation of zonal (σ_U) and meridional (σ_V) velocity, and the dominant period of oscillation of meridional velocity and eddy momentum flux (P)**

	U	V	$U'V'$	σ_U	σ_V	$\sigma_{U'V'}$
V	−0. 40					
$U'V'$	0. 25	0. 06				
σ_U	0. 02	−0. 19	−0. 61			
σ_V	−0. 44	−0. 17	0. 16	0. 43		
$\sigma_{U'V'}$	−0. 07	−0. 64	−0. 32	0. 37	0. 43	
P	−0. 45	0. 03	0. 24	−0. 03	0. 45	0. 10

*All data refer basically to Southern Hemisphere temperate latitudes and to the pressure surface of 200 mb.

velocity covariance (meridional eddy momentum flux). In the average for the year, the poleward eddy flux is (as was evident from fig. 3) a maximum over the South Atlantic when only wave numbers 1–4 are considered. An equatorward eddy flux is found over the southeast Pacific and the Indian Ocean, suggesting a predominance of developing (diffluent) troughs in these regions. Note the considerable (and no doubt coincidental) symmetry of the flux with respect to the Greenwich Meridian. Table 1 indicates that the poleward eddy flux of momentum (negative flux) is largest at the longitudes with the greatest yearly variability in zonal wind ($r=-0.61$).

The light lines in the lower left diagrams of figure 4 show the variation with longitude of the standard deviation of the meridional eddy momentum flux. In accord with figure 3, the yearly variability in flux is greatest near the Greenwich Meridian, with surges of the poleward eddy flux occurring at about 2-mo intervals.

The lower right diagrams of figure 4 give the variation with longitude of the dominant periodicity over the year of the meridional velocity and meridional eddy momentum flux. The dominant periodicity is defined as four times the time lag at which the autocorrelation of the respective parameter first falls to zero. The dominant periodicities so defined are twice as large over the South Pacific as over the remainder of the hemisphere, implying the presence of quasi-permanent circulation patterns in this area. Note from table 1 that the dominant periodicity as expected tends to be large at longitudes where the west wind is weak ($r=-0.45$).

5. TEMPORAL VARIATION OF METEOROLOGICAL PARAMETERS

The variation with time of year of GHOST-derived meteorological parameters is shown in figure 5 where the west and south winds and the eastward-directed phase velocities are considered positive. The middle and bottom diagrams of each set give the approximate contributions of annual and semiannual oscillations to the observed temporal variability. For minimizing any biasing of results

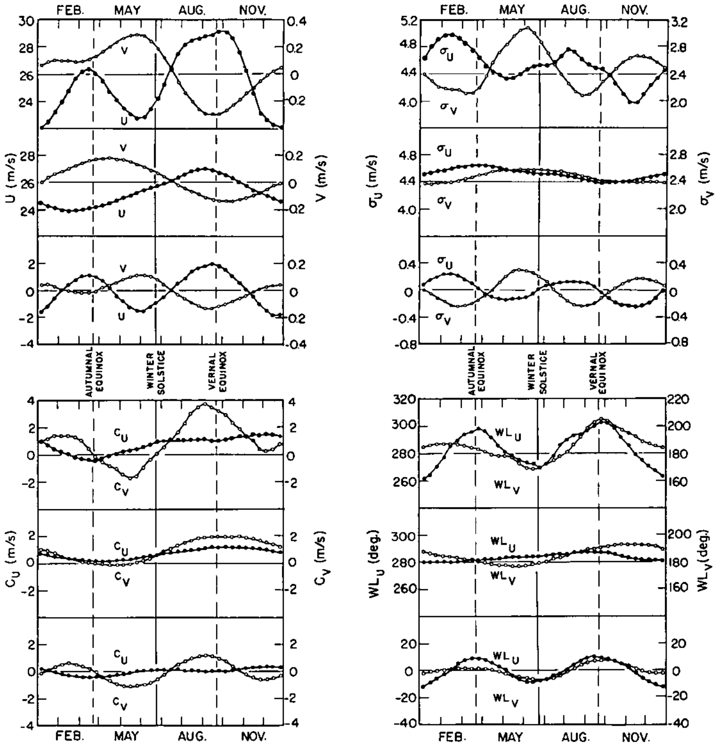

FIGURE 5.—Variation with time of year of the zonal and meridional velocity between 40° and 60°S (upper left set), the standard deviation of zonal and meridional velocity around the hemisphere in temperate latitudes (upper right set), the zonal phase velocity of the waves delineated by zonal and meridional velocities (lower left set), and the dominant wavelengths (deg. long.) determined from the zonal and meridional velocities (lower right set).

because of the large latitudinal excursions of the balloons (fig. 1), only zonal and meridional velocity components in the latitude interval 40°–60°S have been used to estimate the seasonal variation of zonal and meridional wind between June 1, 1966, and June 1, 1967. The other parameters of figure 5 (viz wave speed, dominant wavelength, and velocity standard deviation) have been estimated from the data of figure 3 (i.e., from all the GHOST data regardless of latitude). An estimation of the contribution of the annual harmonic to the temporal variation has been obtained by taking 180-day running averages while the semiannual harmonic has been estimated from the difference between 90- and 180-day running averages. Table 2 shows the ratio of the standard deviations of semiannual and annual variations in velocity and in other derived parameters. The surprising strength of the semiannual oscillation in relation to the annual oscillation (at least in comparison with the Northern Hemisphere) has been previously noted and discussed by Schwerdtfeger (1960), van Loon (1967*a*), and van Loon and Jenne (1969). A possible reason for this relative strength in terms of the momentum budget will be presented in section 6.

The upper left diagram of figure 5 shows the variation with time of year of the 200-mb zonal and meridional velocity between 40° and 60°S. In the case of the annual harmonic, the west-wind maximum occurs about 1 mo

Table 2.—*Ratio of the standard deviations of semiannual and annual variations in the given parameters at 200 mb. The wind and flux values refer to the latitude band 40°–60°S; the remaining parameters refer to Southern Hemisphere temperate latitudes.*

Parameter	*Ratio*
Zonal wind	1.2
Meridional wind	0.6
Standard deviation of zonal wind	1.8
Standard deviation of meridional wind	2.2
Phase speed derived from zonal wind	0.6
Phase speed derived from meridional wind	0.9
Wavelength derived from zonal wind	3.0
Wavelength derived from meridional wind	0.8
Meridional eddy flux of angular momentum	1.0

Table 3.—*Correlations between the variations, with time of year, of west (U) and south (V) winds and the northward eddy flux of momentum ($U'V'$) between 40° and 60° S, the standard deviation of zonal (σ_U) and meridional (σ_V) velocity around the hemisphere in temperate latitudes, and the hemispheric wave speed (C) and dominant wavelength* (WL) *in temperate latitudes derived from time-longitude diagrams of zonal and meridional wind*

	U	V	$U'V'$	σ_U	σ_V	C
V	−0.84					
$U'V'$	−0.31	0.33				
σ_U	−0.04	0.16	−0.73			
σ_V	−0.43	0.57	0.42	−0.56		
C	0.59	−0.77	0.25	−0.24	−0.30	
WL	0.62	−0.63	−0.10	−0.07	−0.54	0.33

prior to the vernal equinox, in general agreement with results for the Northern Hemisphere; van Loon (1965), however, found that, at 500 mb at a given latitude, the west wind was actually strongest in summer although the relatively strong winds extended over a wider latitude band in winter than in summer. Thus, our finding of the strongest west wind near the end of winter may result from the use of zonal wind data throughout the latitude band 40°–60°S.

The GHOST balloon data indicate that the semiannual west-wind maxima at 200 mb between 40° and 60°S occur near the equinoxes; van Loon (1967*b*) has shown from rawinsonde data that the semiannual harmonic is a maximum near 60°S and changes in phase from maximum west wind near the equinoxes poleward of about 45°S to near the solstices equatorward of about 45°S. Thus the rawinsonde and GHOST data are in basic agreement. Note also that quite large semiannual oscillations in zonal wind with west-wind maxima near the equinoxes also occur in the high tropical stratosphere (Angell and Korshover 1970). It would be interesting to see if there is a connection between these two semiannual oscillations.

Of greater interest and possibly of greater significance is the GHOST-derived evidence for an equatorward flow in summer and fall and poleward flow in winter and spring between 40° and 60°S. This implied mean meridional flow has maximum values of 0.3 m/s toward the Equator 1 mo prior to the winter solstice and toward the South Pole near the vernal equinox even though, as mentioned in connection with figure 1, there is considerable variability in meridional drift among the individual flights. In contrast to the findings for the zonal velocity, the semiannual variation in meridional velocity is somewhat less than the annual variation (table 2). The greatest contributors to the mean meridional velocity turn out to be the larger values of the meridional velocity. For example, when the mean meridional velocity is from the north, 64 percent of the 24-hr-average meridional velocities >4 m/s are from the north; but only 53 percent of the meridional velocities between 0 and 2 m/s are from the north. A similar difference holds when the mean meridional velocity is from the south. Thus, the mean meridional velocity tends to result predominantly from "bursts" of relatively large meridional velocities of a given sense; we shall refer to this again in section 6. From momentum and mass balance considerations, both Obasi (1963) and Gilman (1965) found little evidence of a seasonal reversal in mean meridional velocity in the Southern Hemisphere although, by averaging data only for winter (April–September) and summer (October–March), they would tend to mask the variability indicated in figure 5. Also, a reviewer has noted that there may be some errors in the meridional velocity statistics presented by Obasi.

A rather startling feature of figure 5 is the large negative correlation between the variation of west and south winds with time of year ($r=-0.84$ from table 3). Thus when the west wind is relatively strong, the indicated flow is toward the South Pole; when the west wind is relatively weak, the indicated flow is toward the Equator. This association of strong west wind with flow toward the South Pole extends to both annual ($r=-0.76$) and semiannual ($r=-0.86$) oscillations and represents a mechanism for the poleward transport of westerly momentum on a very large time scale.

The representativeness of the GHOST-derived mean meridional flow has been discussed by Solot and Angell (1969*b*). We shall consider the matter further in section 6 with the momentum balance equation. Possible reasons for the meridional drifts, from the synoptic point of view, will also be presented. At this time, we merely point out that the pronounced association of north wind with relatively strong west wind between 40° and 60°S suggests that the speed of the westerlies in these latitudes is not basically governed by meridional drifts of vortex rings with partial conservation of absolute angular momentum because, in such a case, there would be more nearly a 90° phase lag than a 180° phase lag between the two wind components. Furthermore, since the west wind generally increases with decrease of latitude in temperate latitudes, there is for this same reason the implication that the meridional drift is not due to entrainment of the GHOST balloons into the jet stream with consequent poleward and equatorward movement in connection with the seasonal poleward and equatorward movement of the jet.

The upper right diagrams of figure 5 illustrate the variation with time of year of the standard deviation of zonal and meridional velocity around the hemisphere, obtained as the deviation of velocities at 20° intervals from the hemispheric average in figure 3. A large value of the meridional standard deviation implies large values of meridional velocity on the given date or, in general, large-amplitude waves. The standard deviations of zonal and meridional velocity tend to be out of phase ($r=-0.56$ from table 3), particularly in the case of the large semiannual variations, with maxima in wave amplitudes occurring about 1 mo before the solstices. Note also that the meridional velocity or wave amplitude is large when the mean meridional velocity is toward the north ($r=0.57$ from table 3), especially in the case of the semiannual oscillation ($r=0.79$); this bears on our hypothesis regarding the cause of the meridional drifts in section 6. The indicated annual variation in magnitude of the meridional velocity is small, but there is a weak maximum in winter. This small winter-summer difference has been confirmed by other investigators, van Loon (1965) finding that the meridional geostrophic flow was slightly greater in winter than in summer equatorward of 45°S but not poleward thereof and Kao et al. (1970) finding no appreciable difference in wave intensity between winter and summer.

From figure 3, the zonal phase speeds of the waves delineated by maxima and minima of zonal and meridional velocity were estimated from the longitudinal lag that yielded the highest correlation between zonal or meridional velocities 10 days apart around the hemisphere. These phase speeds or wave velocities could only be determined for the entire hemisphere and thus represent a "hemispheric" wave velocity. The lower left diagrams of figure 5 show that the yearly variability in wave speed determined from the meridional velocity is considerably greater than that determined from the zonal velocity although there is a correlation (0.45) between the two. On the basis of the meridional wind, the hemispheric wave velocity for wave numbers 1–4 is a maximum toward the east (nearly 4 m/s) near the vernal equinox and a maximum toward the west (nearly 2 m/s) 1 mo prior to the winter solstice. From an analysis of daily 500-mb maps, van Loon (1965) found that the phase speed of the short waves (say, wave number 6) in middle latitudes is very slightly larger in summer than in winter; but this was not confirmed by Wooldridge and Reiter (1970) using short periods of GHOST data. The GHOST data for the year (fig. 5) indicate an appreciable semiannual contribution to the variation in wave velocity, with the velocity a maximum toward the east about 1 mo before the equinoxes. From table 3, there is a correlation of 0.59 between the zonal wind speed between 40° and 60°S and the phase speed estimated from the zonal and meridional velocity, in agreement with Rossby's equation. This correlation increases to 0.80 when the phase speed is estimated from the meridional velocity alone. There is a high negative correlation between south wind and eastward wave velocity (-0.77 from table 3). This may partly reflect the orientation of troughs and ridges (northwest–southeast in the Southern Hemisphere) associated with the poleward eddy flux of angular momentum. If this is the case, a small portion of the indicated wave velocity (no more than 10 percent as can be seen from the relative magnitude of mean meridional velocity and wave velocity) is not real but is due to the meridional drift of GHOST balloons in "tilted" wave patterns.

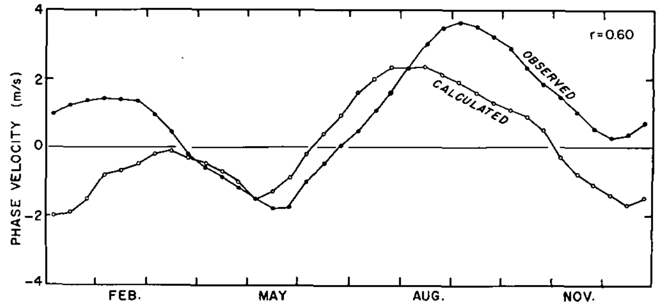

FIGURE 6.—Comparison of the zonal wave velocity (positive toward the east) estimated from the GHOST-derived meridional velocities at 10-day intervals (dots), and the wave velocity calculated from Rossby's equation using the GHOST-derived zonal wind and dominant wavelength (circles).

The dominant wavelengths of the zonal and meridional velocity perturbations were evaluated from figure 3 at 10-day intervals by multiplying by 4 the longitude lag at which the velocity autocorrelations first fell to zero. The lower right diagrams of figure 5 show a pronounced semiannual variation in wavelength, with the maximum wavelength occurring near the equinoxes. Table 3 shows, as expected, a fairly high correlation of 0.62 between dominant wavelength and west-wind speed; but it also shows a positive correlation (0.33) between wavelength and wave speed in contradiction to Rossby's equation. To show more clearly how zonal wind and wavelength combine in Rossby's wave equation, we present in figure 6 a comparison of the hemispheric wave speed (obtained from the meridional velocity) with the wave velocity (C) obtained from Rossby's equation expressed as

$$C=U-\frac{(\beta L^2/4\pi^2)}{(1+L^2/d^2)} \tag{1}$$

where U is the mean zonal wind (upper left diagram of fig. 5); L is wavelength (heavy line at lower right in fig. 5); β is the latitudinal variation of the Coriolis parameter; and d is a measure of the latitudinal extent of the wave, taken equal to 10^4 km in agreement with Kao and Wendell (1970). There is satisfactory agreement between observation and theory, both in the sense of overall magnitude and in the sense of providing a significant correlation (0.60) between observed and calculated variations in wave velocity with time of year.

6. INFERRED MEAN MERIDIONAL VELOCITY AND MOMENTUM BALANCE

As indicated earlier, of fundamental importance is the representativeness of the GHOST-derived mean meridional velocity. An appropriate mechanism to establish the representativeness, or otherwise, of this mean meridional velocity is through consideration of the momentum flux

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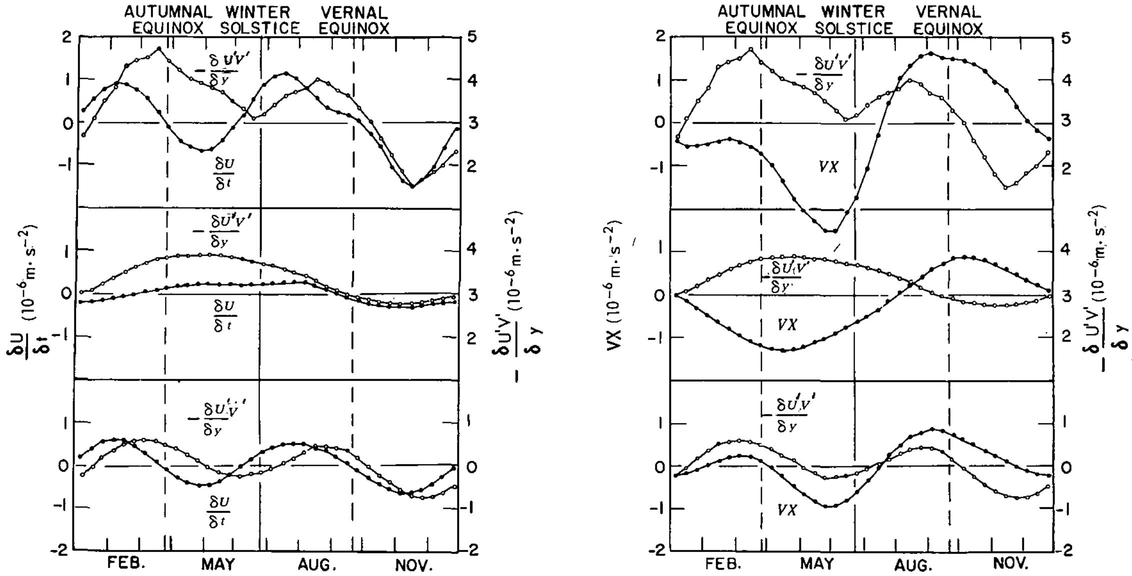

FIGURE 7.—Variation with time of year of the zonal wind acceleration between 40° and 60°S and convergence of the meridional eddy momentum flux between 40° and 60°S (left set), and a comparison between the eddy momentum flux convergence and the momentum changes due to the advection of relative zonal velocity by the mean meridional flow (right set) for this same latitude band.

that would result if such a meridional velocity really exists and the manner in which the flux associated with this mean motion collates with the eddy fluxes.

The rate of change of the zonal velocity ($\partial U/\partial t$) in a latitude ring removed from the earth's surface may be expressed by

$$\partial U/\partial t=-\frac{\partial}{\partial y}\,(U'V')+V\left(\frac{U}{a}\,\tan\phi-\partial U/\partial y\right)$$
$$+Vf-\frac{\partial}{\partial z}\,(U'W')-W\partial U/\partial z \quad (2)$$

(Mintz 1955) where the first term on the right represents the effect on the zonal wind within the ring of the convergence of the meridional eddy flux of momentum; the second term represents the effect resulting from the advection of a latitudinally varying zonal wind by the mean meridional velocity plus a contribution due to the convergence of the meridians (a is the earth's radius, and ϕ is the latitude); the third term represents the far larger effect caused by meridional advection of earth angular momentum (f is the Coriolis parameter, and this term is frequently called the Coriolis torque term); the fourth term represents the effect of the convergence of the vertical eddy flux of momentum; and the last term represents the effect of vertical advection in a wind field varying in strength with height. Our lack of knowledge of the vertical velocity field prohibits the last two terms from being evaluated here. Given this unfortunate omission, let us see if there is any evidence from the momentum balance equation for the reality of the GHOST-derived mean meridional velocities.

The meridional eddy flux of westerly momentum has been estimated as a function of latitude and date from the GHOST data by forming the covariance of the deviation of 24-hr-average zonal and meridional velocities from the monthly mean and plotting the resulting covari ances as a function of latitude and date. Because of the considerable underestimate of the meridional velocity due to the 24-hr smoothing (as mentioned previously), the GHOST-derived meridional momentum flux must be greatly underestimated; this is seen to be so by comparison with the results obtained by Obasi (1963, 1965) from rawinsonde observations. However, the variation of the GHOST-derived flux with latitude and date may still be representative of the variation actually occurring.

The upper left diagram of figure 7 shows the temporal change in GHOST-derived west wind between 40° and 60°S and, in similar units, the change in speed that would be anticipated from the GHOST-derived meridional convergence of the eddy momentum flux between 40° and 60°S. A correlation of 0.63 exists between the two terms, suggesting that an appreciable part of the yearly alternation in west wind can be explained by the yearly alternation in eddy flux convergence. However, despite the underestimate of the meridional velocity, the eddy flux convergence is considerably larger than that required to change the west wind by the given amount; and in particular, there is always an eddy flux convergence even when the west wind is decreasing. Any influence of the inferred mean meridional velocity on the momentum flux should help explain these discrepancies.

The two bottom diagrams at the left in figure 7 show the breakdown of the temporal variations of these two terms into annual and semiannual harmonics. The temporal variation of the two terms is nearly in phase in the case of the annual oscillation ($r=0.89$); but as indicated above, the amplitude of the eddy flux convergence is considerably larger than the acceleration of the west wind. In the case of the semiannual oscillation, the amplitudes are similar; but there is a phase lag, with the change in west wind slightly preceding the eddy flux convergence and divergence ($r=0.61$).

In eq (2), look at the contribution to the momentum equation of the second term on the right (i.e., the meridional advection of a zonal wind varying with latitude plus the effect of the convergence of the meridians). Both terms depend directly or indirectly on the product of zonal and meridional velocity and thus could be of rather large magnitude because of the correlation already found between zonal and meridional velocity (upper left diagrams of fig. 5). The right side of figure 7 shows a comparison between the sum of these two advection terms (henceforth called the relative advection term, denoted by VX in fig. 7) and the convergence of the eddy momentum flux. The relative advection term helps greatly in explaining the decrease in west wind between the autumnal equinox and the winter solstice; from this point of view, the GHOST-derived northward velocity at this time of year appears reasonable. Of perhaps greater importance is the observation (two bottom diagrams at right) that the relative advection and flux convergence terms are almost out of phase when the annual oscillation is considered ($r=-0.95$) but tend to be in phase when the semiannual oscillation is considered ($r=0.38$). This would help explain the relatively large semiannual variation in zonal wind in comparison with the annual variation between 40° and 60°S; from this point of view, the GHOST-derived meridional velocities again appear reasonable.

Problems arise, however, when consideration is given to the effect on the momentum equation of the Coriolis torque term [third term on the right in eq (2)]. This term is of course highly correlated with the relative advection term ($r=0.98$) and, when given the GHOST-derived meridional velocities, would be two orders of magnitude larger than the other three terms presented in figure 7. This large contribution can be offset only by the last two terms in eq (2) involving the vertical velocity, of which we know nothing. It is important to recall, however, that the Coriolis torque term is different from the other terms heretofore considered in that it can have an effect across a latitude *wall* only if there is a net mass exchange across the wall; otherwise, the Coriolis torque effect where the flow is poleward will be compensated at another level where the flow is equatorward. As a consequence, if the atmosphere in Southern Hemisphere temperate latitudes has the capability of efficiently transporting momentum in the vertical, either by means of eddy fluxes or mean vertical motions, then the effect of the Coriolis torque term at any particular level may be negligible.

7. POSSIBLE SYNOPTIC PATTERNS RESPONSIBLE FOR MEAN MERIDIONAL FLOWS

Given the possibility that the mean meridional velocities delineated by the GHOST ballons are real and serve to help balance the momentum equation, we immediately have the question as to why the eddy momentum flux alone does not manage to balance the equation. A tentative answer to that question appears when we consider, from a synoptic point of view, how these mean meridional flows may be generated.

Let us assume a situation in which the poleward eddy momentum flux is for some reason excessive. The establishment of a series of diffluent troughs would counteract this excessive poleward flux. However, as shown by Angell (1962) from an analysis of transosonde flights, inertial instability is occasionally established on the anticyclonic shear side of a pronounced diffluent trough, leading to a large displacement of air parcels toward high pressure and low latitude. Since there is no other location in the wave pattern where geostrophic control is so obviously lost, this type of wave pattern could lead to a net equatorward flow when the meridional velocities are summed around the hemisphere. In this case, the eddy momentum flux is augmented by the flux resulting from the mean meridional velocity, in that both terms serve to transport momentum equatorward. Accordingly, it may be better to think of the momentum flux associated with the mean meridional velocity not as a replacement for the eddy momentum flux but rather as a natural companion to the eddy flux (i.e., a mean meridional velocity results more or less automatically when nature attempts to redress the momentum balance by means of the eddy flux).

Some confirmation for this hypothesis is found in the correlations from table 3 of 0.57 between wave amplitude and northward flow, -0.77 between wave speed and northward flow, and -0.63 between wavelength and northward flow since, according to Bjerknes (1951), large-amplitude short waves moving slowly eastward frequently fall into the "unstable ridge" category that leads to the development of diffluent troughs and, according to the hypothesis of the preceding paragraph, equatorward or (in our case) northward-directed mean meridional flows. Further confirmation is provided by the earlier finding that mean meridional velocities result mostly from bursts of relatively large meridional velocities of given sign (sec. 5), which would seem to be in accord with the concept of intermittently occurring inertial instability.

The synoptic patterns responsible for poleward drifts of air are not so obvious. It is suggested that strongly confluent troughs may lead to a poleward drift in the mean around the hemisphere because, as the air upwind and equatorward of the jet maximum accelerates and moves toward low pressure, it may continually encounter a pressure gradient that remains in excess of the continually increasing Coriolis force. In this case also, the momentum flux resulting from the meridional flow would augment the eddy flux. Thus while we are able to suggest synoptic patterns responsible for the augmentation of the eddy flux of momentum by the mean meridional velocity, as indicated by the semiannual variations at the right in figure 7, we have not yet been successful in deducing the synoptic patterns responsible for the opposition of the two terms as illustrated by the annual variations in figure 7.

8. CONCLUSIONS

Constant-level balloons furnish useful information for atmospheric circulation studies because the resulting data sample is relatively uniform at all longitudes around the hemisphere. However, the GHOST flights examined here did not provide a uniform data sample with respect to latitude because of the more poleward float latitude of the balloons in summer. For comparison with the results presented herein, we await with interest the results to be obtained from further GHOST flights in the Southern Hemisphere and the results to be obtained from the large-scale EOLE experiment to be carried out by the French in Southern Hemisphere temperate latitudes in the autumn of 1971 (Morel 1969).

Of particular importance in any continuing study is the question of the relatively large mean meridional velocities inferred from the nine GHOST balloon flights of this paper since there is little observational evidence in the Northern Hemisphere for such large meridional drifts and most theoretical studies using conventional data also do not disclose the presence of such drifts. If fairly large mean meridional velocities truly exist in Southern Hemisphere temperate latitudes, as now seems possible, some reorientation in the thinking of persons engaged in general circulation studies may be required.

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